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THESIS

AN INVESTIGATION OF NEAR-BOTTOM CURRENTS IN
THE MONTEREY SUBMARINE CANYON

by

John Joseph Dooley

June 1968

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AN INVESTIGATION OF NEAR-BOTTOM CURRENTS IN THE MONTEREY SUBMARINE CANYON

by

John Joseph Dooley
Lieutenant, United States Navy
B.A., Boston College, 1958

Submitted in partial fulfillment of the
requirements for the degree of
MASTER OF SCIENCE IN PHYSICAL OCEANOGRAPHY
from the
NAVAL POSTGRADUATE SCHOOL
June 1968

Signature of Author John J. Dooley

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Thesis D6495 c.2

ABSTRACT

An investigation of near-bottom currents in the head of Monterey Submarine Canyon was conducted between March 1967 and May 1968. Continuous observations of water temperature, current speed and direction were obtained over periods ranging from 5 hours to 162 hours using an in situ Savonius rotor current measuring system. Basic statistical parameters and power spectra were calculated for each record. These revealed an average current speed of about 0.23 knots (standard deviation of 0.17 knots), and a current direction which indicates flow reversals predominantly along the canyon axis. Current and water temperature oscillations indicated a strong semidiurnal component. Water temperature changes also showed seasonal variation that agrees with the seasonal means of the region. Current speeds as high as 1 knot were measured.

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LIST OF SYMBOLS

X_i'	i^{th} value of discrete, equi-spaced time series, $X(t)$.
n	number of discrete data points
m_x	mean of data
$R_x(p)$	Autocovariance of series X at lag p.
p	Lag
m	Maximum Lag
$A_x(p)$	Autocovariance of series X after detrending at lag p.
$P_x{}^{(h)}$	Power spectral estimate of series X at frequency $\frac{h\pi}{m\Delta t}$
ϵ_p	the lag window
$SP_x{}^{(h)}$	Smoothed power spectral estimate of series X at frequency $\frac{h\pi}{m\Delta t}$
ν	number of degrees of freedom
$\chi_\nu{}^2$	Chi-squared distribution at ν degrees of freedom.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation and thanks to Professor Warren W. Denner, Naval Postgraduate School, for his continued patience and advice throughout the course of this investigation. Sincere thanks is due also to Mr. Donald F. Keene, oceanographic technician at the Naval Postgraduate School. Mr. Keene, through his experience with the equipment and his enthusiastic response, provided invaluable assistance to the author during the measurement phase of the investigation.

I. INTRODUCTION

Purpose of this Investigation

This investigation was undertaken in order to accurately measure the velocity of near-bottom currents in the Monterey Submarine Canyon. In the past, quantitative knowledge of the water motion within submarine canyons has been obtained, almost exclusively, using Ekman type current meters. Continuous recordings of currents in canyons over several day periods are conspicuously missing from present day oceanographic knowledge. This paper presents the results obtained from continuous recording Savonius current meters, placed 15 meters above the bottom in depths of 125 to 165 meters at the head of the Monterey Submarine Canyon.

Background.

The factors influencing current motions in submarine canyons have been little studied even though a few investigators have succeeded in obtaining accurate velocity measurements. Stetson (1936), using an Ekman type meter, made direct current measurements in three canyons on the Georges Bank. His observations showed that the canyon currents had a predominantly tidal character.

Currents between .2 and 1.25 meters above the bottom of several Southern California canyons were measured by Shepard, Revelle, and Dietz (1939) using an Ekman type current meter. While the main purpose of the latter investigators was to determine the maximum currents in the canyons, they did note that, although exhibiting some tidal components, the bottom currents appeared to be non-tidal in character.

In later investigations of the Scripps Canyon, Shepard has reported currents as high as 10 cm/sec flowing in a down-canyon direction. Possible explanations of the origin of the currents are surf beat, or internal waves, or possibly seaward return flow of water carried inshore by swell (Shepard, et al,1964).

Gatje and Pizinger (1965) reported current speeds as high as 0.8 knot at 4.8 meters above the bottom of Monterey Canyon. Using an Ekman type current meter, they observed that the currents follow the canyon axes with a seaward (down-canyon) flow during the rising tide, and a coastward (up-canyon) flow during the falling tide.

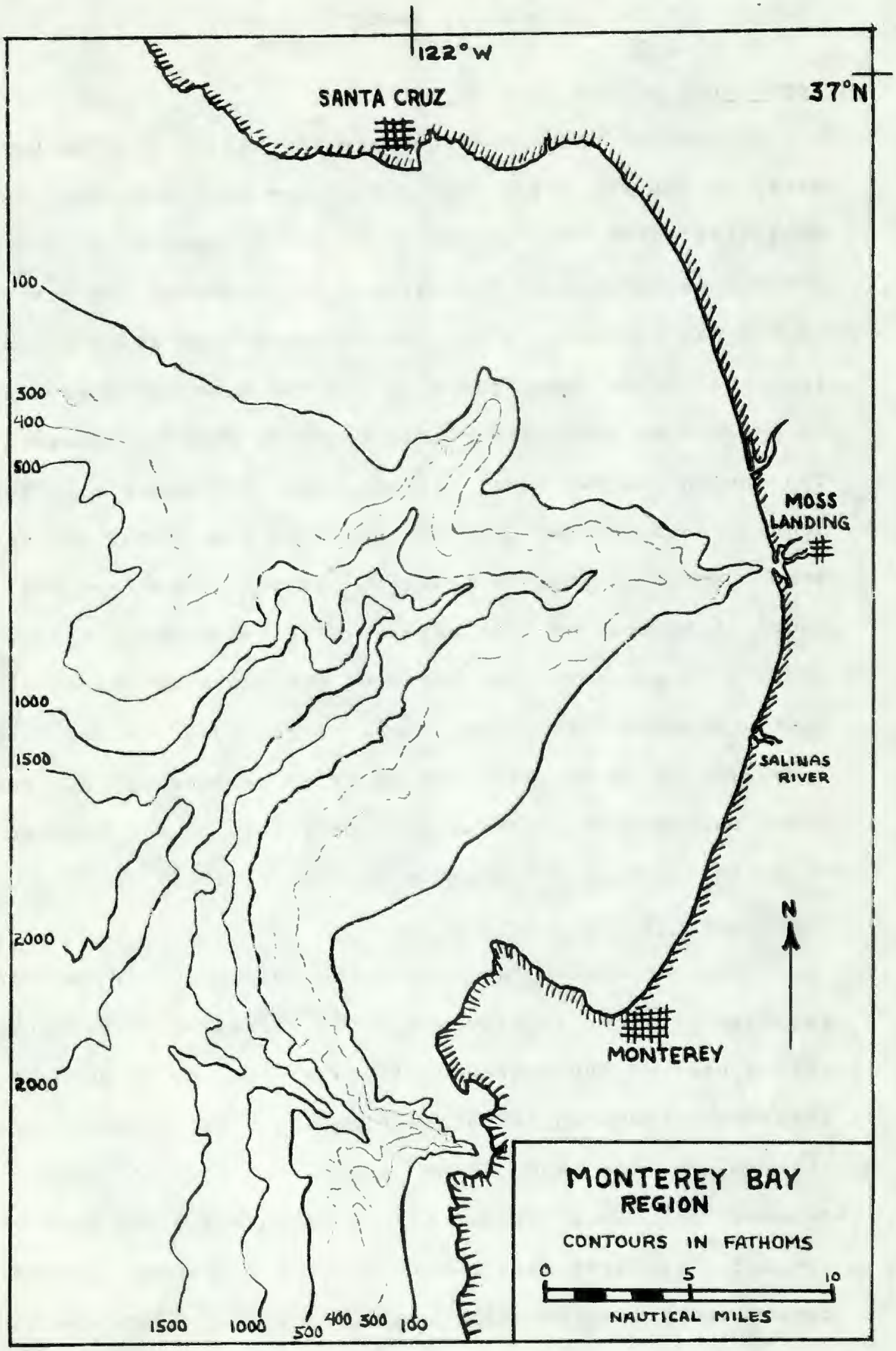

Figure 1. Monterey Bay Region

II. AREA OF INVESTIGATION

Topography of Monterey Bay

Figure 1. shows the Monterey Bay Region and the bathymetry of the Bay and Canyon. Monterey Bay is in open communication with the Pacific Ocean and is subject to the oceanic variations of the California current. The bottom of the Bay is cut by a massive canyon system which extends from the Canyon head, one mile off the coast at Moss Landing, to a depth of 3000 meters at a point 50 miles to seaward. The canyon has two major tributaries. The seven mile long Soquel Canyon enters from the north at a depth of 950 meters. Carmel Canyon, 16 miles in length, joins from the south at a depth of 2000 meters. The relatively shallow shelves to the north and south of the Monterey Canyon slope gently seaward. The side slopes of the Canyon range from 5 degrees to 34 degrees with an axial gradient of 8.5 degrees at the head, decreasing irregularly to 0.5 degrees 30 miles to seaward. (Martin and Emery, 1967)

Topography of the Canyon Head

A more detailed picture of the topography of the Canyon Head is shown in Figure 2. The fairly uniform channel at the base of the V-shaped canyon starts to broaden at about 90 fathoms while maintaining a 3.5 degree axial gradient up into the head of the canyon. At a depth of 65 fathoms the channel splits into a north and south fork while the axial gradient steepens to about 8.5 degrees. These two channels continue east roughly parallel up to the 5 fathom contour. The Canyon head is about 450 meters wide and 750 meters in length from the 5 fathom contour to the beginning of the well defined channel at 90 fathoms. The Canyon comes into the shore near the breakwater at Moss Landing. The canyon axis between 65 and 90 fathoms roughly trends 070-250 degrees true.

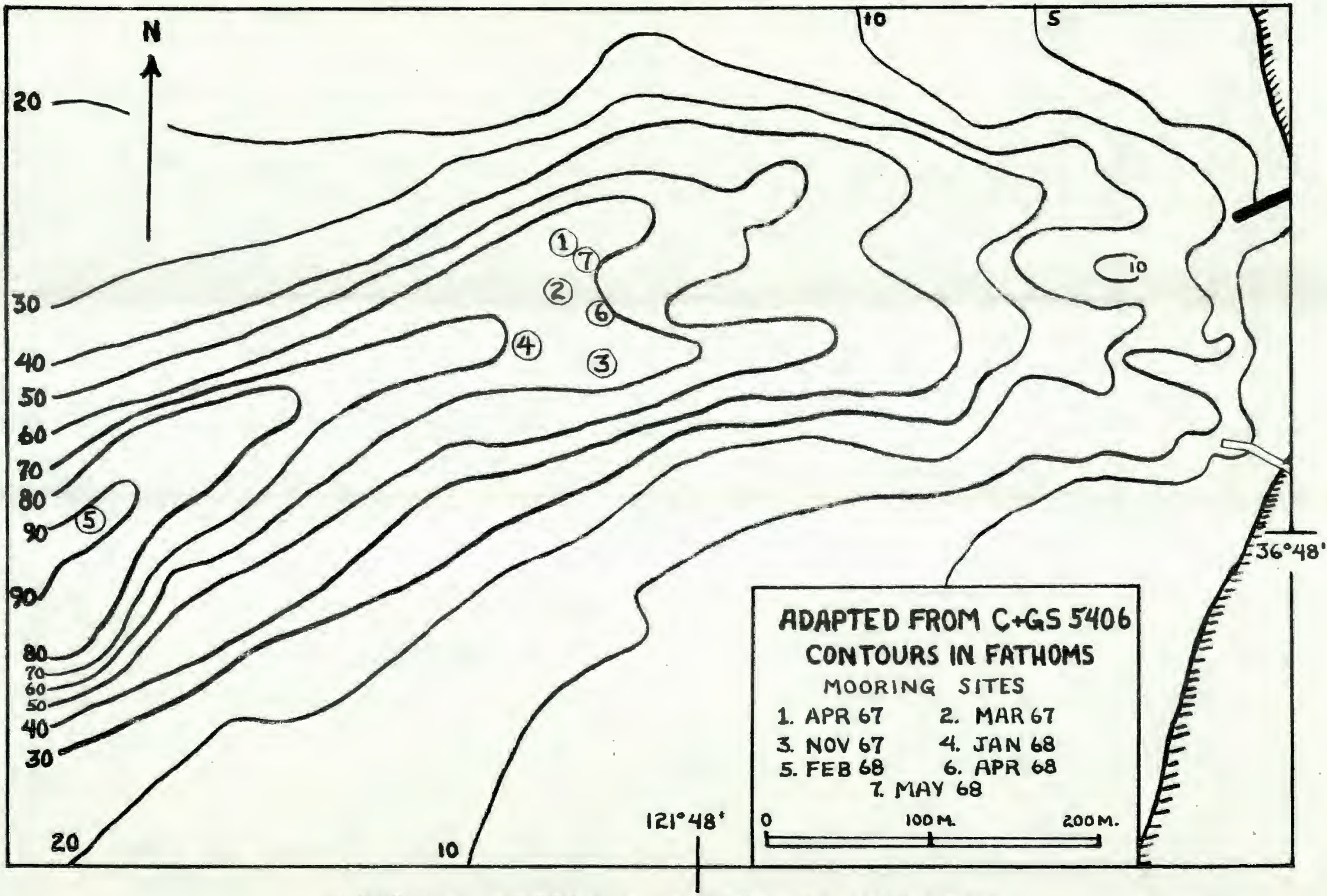

FIGURE 2. TOPOGRAPHY OF THE CANYON HEAD

III. OBSERVATION PROCEDURES AND EQUIPMENT

The Taut Wire Mooring

A total of nine moorings were established in the Canyon during the course of this investigation. Actual locations of the moorings are shown in Figure 2. The February 1968 mooring was placed further down the Canyon axis to investigate how the flow varied along the Canyon axis.

Experimentation with various taut wire moorings in March and April 1967 resulted in the design of the basic taut wire mooring system that was used with little modification throughout the observational program. The taut wire mooring is shown in Figure 3. The Navy 63 foot Hydrographic Research Vessel was used for the launching and recovery of all moorings.

The mooring consisted of an expendable section and a recoverable section. The expendable section consisted of an anchor and mooring line. The anchor was a 55 gallon cement filled oil drum. It was connected to the recoverable section by a timed release with 5 meters of 3/8 inch nylon line. The recoverable section was made up of the release mechanism, 10 meters of 3/8 inch polypropylene line, the Savonius rotor current measuring system, 10 meters of 3/8 inch polypropylene line, and the buoyancy-recovery float. Swivels were inserted at each shackle connection to allow free rotation. Buoyancy was provided by three 18 inch glass floats. A large vane (2 feet by 3 feet) and a meter mounting frame were constructed to relieve the strain on the current measuring system,

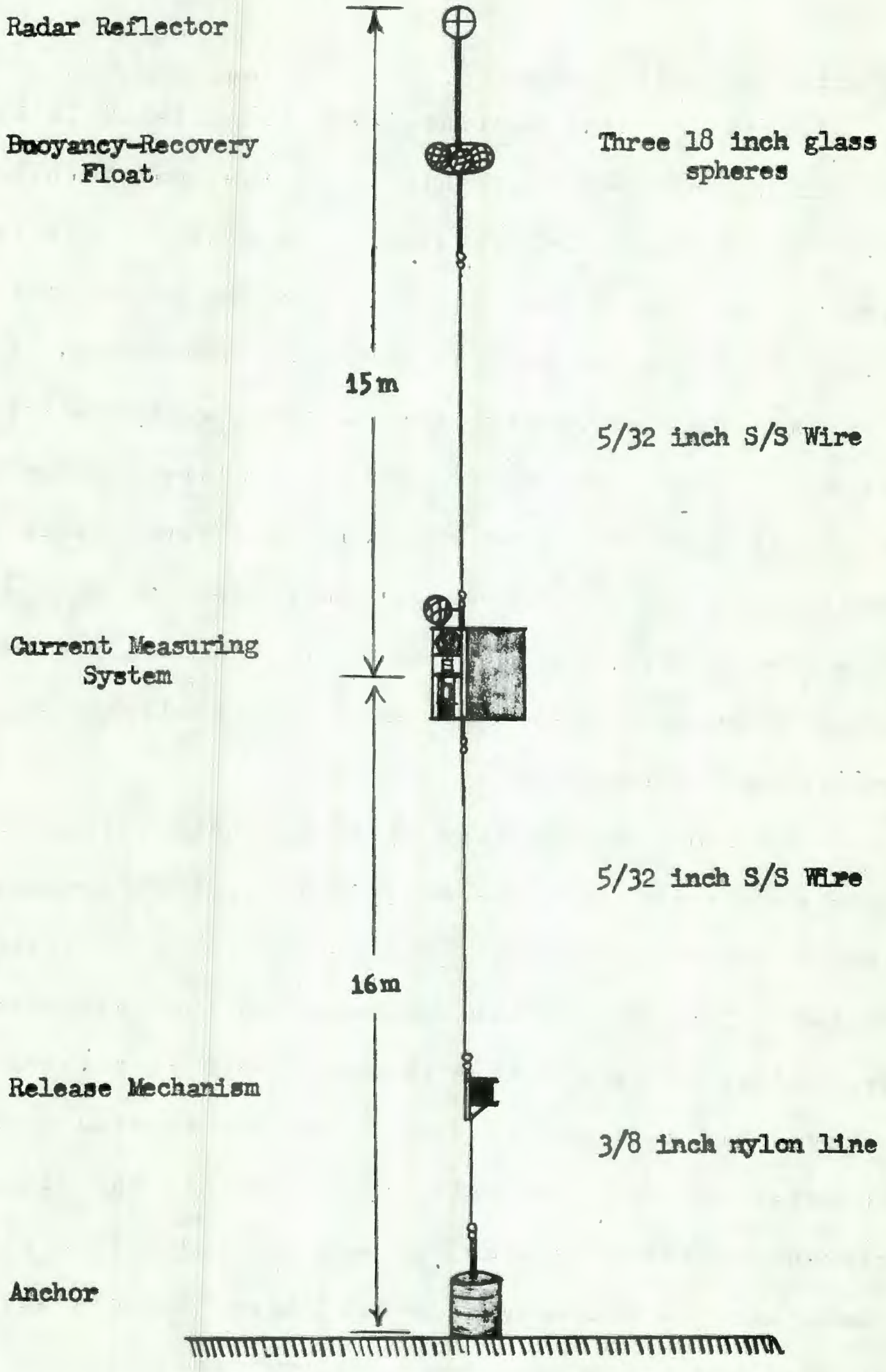

Figure 3. The Taut Wire Mooring

and to provide rotational stability. The stabilizer vane was balanced by a fourth 18 inch glass float attached opposite the vane.

Difficulties in recovering the January mooring led to some modifications of the mooring rig. The anchor weight was increased from 300 to 540 pounds and the two 10 meter polypropylene lines were replaced with two 10 meter 5/32 inch stainless steel wires.

The Current Measuring System

The sensor used in this investigation was a Model 501B Savonius current meter, manufactured by Hydro Products, San Diego, California. Specifications mentioned in this section are furnished by the manufacturer. The system includes a Savonius rotor, direction vane, thermistor and electronics sphere.

The Savonius rotor, mounted on carbide to carbide bearings, rotates at an angular rate proportional to the speed of the water flow. The rotation rate is determined from a magnetic pick-up whose output is a pulsed DC voltage. Accuracy of the speed measurement is ± 3 per cent of the reading over the range of .05 to 7.0 knots. A satisfactory linearity check of the output of the two rotors used was made in April, 1968. (Figure 4)

Current direction is measured with reference to magnetic north. A magnetic compass, located under the vane, is magnetically coupled to the slider of a low torque potentiometer. By applying fixed voltage across the potentiometer the voltage output on the slider is proportional to the degree of travel from magnetic north. Accuracy of the direction value is ± 5 degrees.

The thermistor is embedded within the aluminum housing of the electronics sphere. It is accurate to within ± 3 per cent of the value over a range of zero to 40 degrees Celsius. The thermistor stability is less than one per cent error in 24 hours.

The electronics sphere contains the electronic circuitry, Rustrak two inch strip chart recorder, six volt nickel cadmium battery and clock timer. Current speed readout circuitry consists of a pulse rate counter which generates a DC voltage proportional to the number of pulses received from the rotor. This DC level is recorded as current speed. Current direction readout is the amplified DC voltage from the compass slider. Water temperature is recorded on the strip chart as a measure of the DC level from the thermistor bridge. The three DC outputs are applied through a switching system to the recorder.

The current meter weighs 38 pounds in sea water and its frame is 102 cm. in length by 40 cm. in width. Table I is a summary of the manufacturer's measuring system specifications.

The Release Mechanism

A timed release, the Braincon 422 release mechanism, manufactured by Braincon Corporation, Marion, Massachusetts, was used to permit the measuring system to return to the surface for recovery. After the timer counts down to the preset release time an explosive squib is activated which

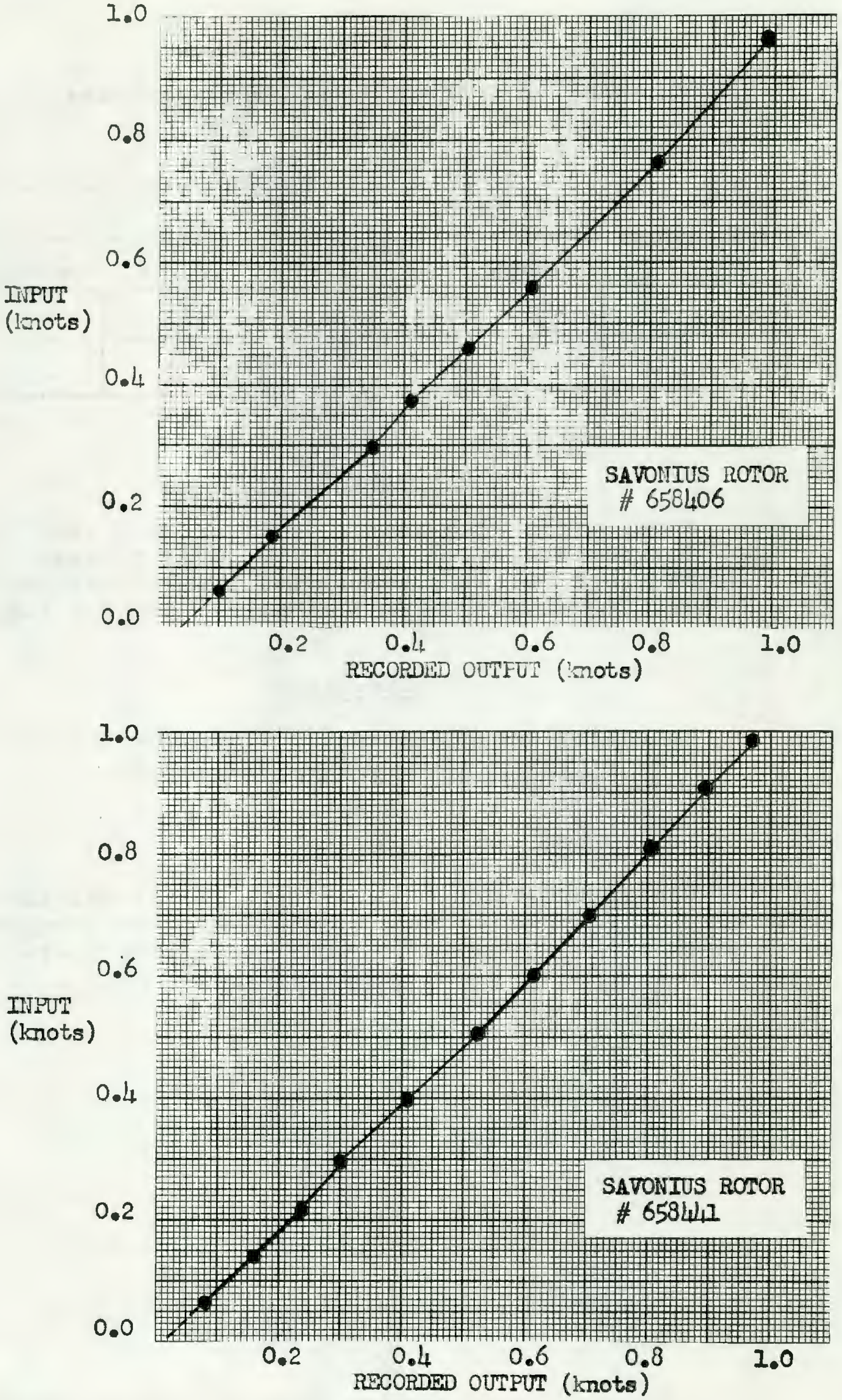

Figure 4. Linearity Check of the Savonius Rotors.
(input speed determined by equivalent rotor revolutions)

TABLE I

Savonius Current Meter Specifications

	Speed	Direction	Temperature
Range	0.05-1.0 kts.	353 (± 2)°	0 - 40° C.
Accuracy	± 3%	± 5°	± 3%

Savonius Rotor

Revolutions at 1 knot	83.5 RPM
Threshold	0.05 Knot
Contruction	Polystyrene rotor in 304 S/S housing

Compass

Potentiometer resistance	10K ohms ±5%
Linearity	0.1%

Thermistor

Linearity	±2% maximum derivative from straight line characteristics.

allows the release to disengage from the mooring line. The weight of the release in water is 17 pounds.

Mooring Procedure

Navigation was by radar and visual fixes on numerous navigational aids in the Moss Landing area. Depths were determined using a Precision Depth Recorder. At the mooring site the array was launched by lowering the recoverable portion of the moor into the water. The vessel was then precisely positioned over the desired canyon location and the weight launched. Table II, a summary of the observation program, contains positions and depths of the moorings.

TABLE II

Observation Program

START/FINISH TIME (Local)	RECORD LENGTH	POSTION	DEPTH	REMARKS/ MALFUNCTIONS
221000 Mar 67 to 241340 Mar 67	50 hrs.	36°48.09'N 121°48.53'W	119 m.	Testing Taut-Moor
101048 Apr 67 to 111454 Apr 67	28 hrs.	36°48.10'N 121°48.60'W	121 m.	Testing Taut-Moor with surface recovery buoy.
241110 Nov 67 to 262210 Nov 67	56 hrs.	36°48.15'N 121°48.40'W	128 m.	Ceased recording at 262210, normal recovery at 272310 Nov 67.
151426 Jan 68 to 212326 Jan 68	153 hrs.	36°48.10'N 121°48.60'W	133 m.	Recovered buoyancy float by dragging 201500 Jan 68. Recovered meter by dragging 081400 Feb 68. Squib failed to fire after clock time expired.
290945 Feb 68 to 021410 Mar 68	52 hrs.	36°47.92'N 121°51.05'W	165 m.	Recovered in surf off Moss Landing 20 Mar 68. Time release failed to disengage after squib fired. Speed rotor malfunction after 52 hrs.
181610 Apr 68 to 251439 Apr 68	5 hrs.	36°48.18'N 121°48.18'W	110 m.	Meter malfunction, launched with difficulty in heavy seas.
301307 Apr 68 to 071436 May 68	0 hrs.	36°48.18'N 121°48.15'W	95 m.	Meter malfunction, electronics failure
071515 May 68 to 141428 May 68	0 hrs.	36°48.19'N 121°48.20'W	108 m.	Meter malfunction, electronic failure.
141520 May 68 to 211526 May 68	162 hrs.	36°48.08'N 121°48.52'W	104 m.	Normal recovery at 211535 May 68.

IV. DATA ANALYSIS

Sampling Procedure and Data Reduction

The Rustrak recorder provided a record of temperature, speed, and direction with time. The recording cycle of the current measurement system is 7.5 minutes, during which speed and temperature inputs are recorded for a period of 1.5 minutes, then the input is switched to speed and direction for 5 minutes. Each input is recorded every 4 seconds. Upon completion of the speed/direction cycle the recorder then starts another cycle by switching to the speed/temperature input. As a result of this switching sequence, during each cycle 6.5 minutes of speed values, 1.5 minutes of temperature values, and 5 minutes of direction values are recorded.

A sampling interval of 3.75 minutes (.0625 hours) was used to convert the record to digital form, except for temperature which was sampled every 7.5 minutes. This sampling interval allowed analysis of frequencies between zero and 0.133 cycles per minute, the "cut-off" or Nyquist frequency. Transfer of the readings to IBM punch cards was done by personnel at the Postgraduate School Computer Facility. The data was then run through a data adjustment and listing computer program which inserted an interpolated temperature for every other temperature data point and converted the magnetic directions to true directions.

Elementary Statistics

"CURRENT"*, a FORTRAN IV computer program, was then written to compute and display the following statistics of the temperature,speed, and direction time series:

---

*Appendix A

(1) Hourly means

(2) Daily means, medians, modes, and frequency distributions

(3) Time series means, medians, modes, variances, standard deviations and frequency distributions

(4) A graphical output of the three time series and the frequency distributions.

These elementary statistics were computed using standard techniques with the exception of direction means which were computed by the method of Webster (1964).

Power Spectra Analysis

Spectral analysis was applied to the individual time series to divide the variance of the time series into discrete frequency bands. The power spectrum provides a measure of the density of the variance as a function of frequency. Power spectral computations were done using computer program BMDO2T, written by Health Science Associates, UCLA.

Power Spectra Computational Procedure

For the observed discrete time series X_i', $i=1,2,..,n$, the mean (m_x) is computed.

$$m_x = n^{-1} \sum_{i=1}^{n} X_i' \qquad \text{(I)}$$

where n is the number of discrete values in the series.

The autocovariance ($R_x(p)$) is then computed from the equation:

$$R_x(p) = \frac{1}{n-p} \sum_{q=1}^{n-p} X_q' X_{q+p}' \quad , p = 0,1,2,\ldots,m \qquad \text{(II)}$$

where m is the maximum number of lags.

A detrending algorithm is applied to remove the very long period trends.

$$A_x(p) = R_x(p) - m_x^2 - \frac{1}{12}\lambda_p \alpha_x^2 \qquad \text{(III)}$$

where: $p = 0,1,2,\ldots,m.$

$$\lambda_p = (n\Delta t)^2 \left[1 - 2\left(\frac{p}{n}\right) - 2\left(\frac{p}{n}\right)^2\right]$$

$$\alpha_x = \frac{1}{k(\Delta t)(n-k)}\left[\sum_{i=n-k+1}^{n} X_i' - \sum_{i=1}^{k} X_i'\right]$$

Δt is the sampling interval

k is the integer part of $\frac{n+2}{3}$

$A_x(p)$ is the autocovariance of the series X after detrending.

The raw estimates of the power spectrum are obtained by:

$$P_x(h) = \frac{2\Delta t}{\pi}\sum_{p=0}^{m} \epsilon_p A_x(p) \cos\frac{hp\pi}{m} \qquad \text{(IV)}$$

where: $h = 0,1,2,\ldots,m.$

$$\epsilon_p = \begin{cases} 1, & 0 < p < m \\ \frac{1}{2}, & p = 0, m \end{cases}$$

The raw estimates of the power spectrum are then smoothed by "hamming":

$$\begin{aligned} SP_x(o) &= .54\,P_x(0) + .46\,P_x(1) \\ SP_x(h) &= .23\,P_x(h-1) + .54\,P_x(h) + .23\,P_x(h+1), \quad 0 < h < m \qquad \text{(V)} \\ SP_x(m) &= .54\,P_x(m) + .46\,P_x(m-1) \end{aligned}$$

where $SP_x(h)$ is the smoothed power spectrum.

The smooth estimate of the power spectrum has a chi-square distribution with ν degrees of freedom. According to Blackman and Tukey (1958), the degrees of freedom for a discrete time series may be approximated by:

$$\nu = \frac{2n}{m} \qquad \text{(VI)}$$

where n is the number of data points and m is the maximum number of lags.

Borgman (1967), according to Collins (1967), gives the 90% confidence interval as:

$$\left[\frac{SP_x(f)}{\chi^2_\nu(0.95)} , \frac{SP_x(f)}{\chi^2_\nu(0.05)} \right] \qquad \text{(VII)}$$

V. RESULTS

Seven records of temperature, current speed and direction were obtained during the investigation. The April 1968 record is not suitable for analysis since it contains only five hours of data.

Summary

The computer drawn graphical displays of the November 1967, January 1968, February 1968, and May 1968 records are reproduced in Figures 5 through 8. The cyclic character of the temperature record is more readily distinguished than that of the direction and speed records. Considerable noise is evident in the direction records since the direction vane tends to "hunt" at low current speeds. Visual correlation of the individual records show that, in most instances, an increase in current speed is accompanied by a decrease in water temperature. The regular bursts of high speed current seem to occur consistently in an up-canyon direction. This relationship is not present in all records, but would tend to indicate movement of colder water up the Canyon head.

The frequency distributions of temperature, speed and direction are shown in Figures 9, 10 and 11 respectively. The temperature distributions reflect the seasonal nature of the Monterey Bay waters. A narrow distribution of cold water (8 - 10°C) is evident in February, March, April and May. The temperature distribution in November and January is quite wide (8 - 14°C) and shows much warmer temperatures.

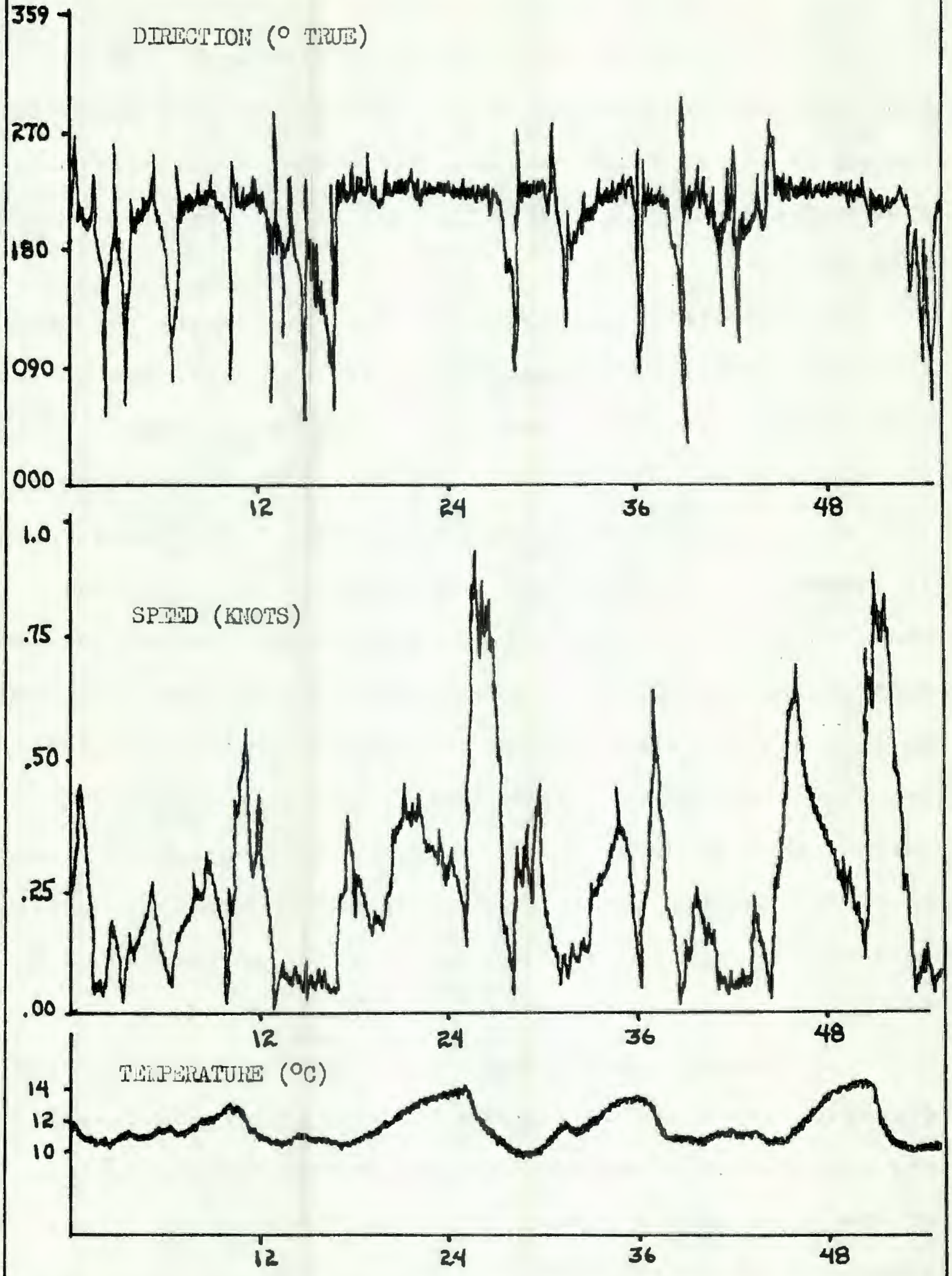

Figure 5. Display of November 1967 Time Series

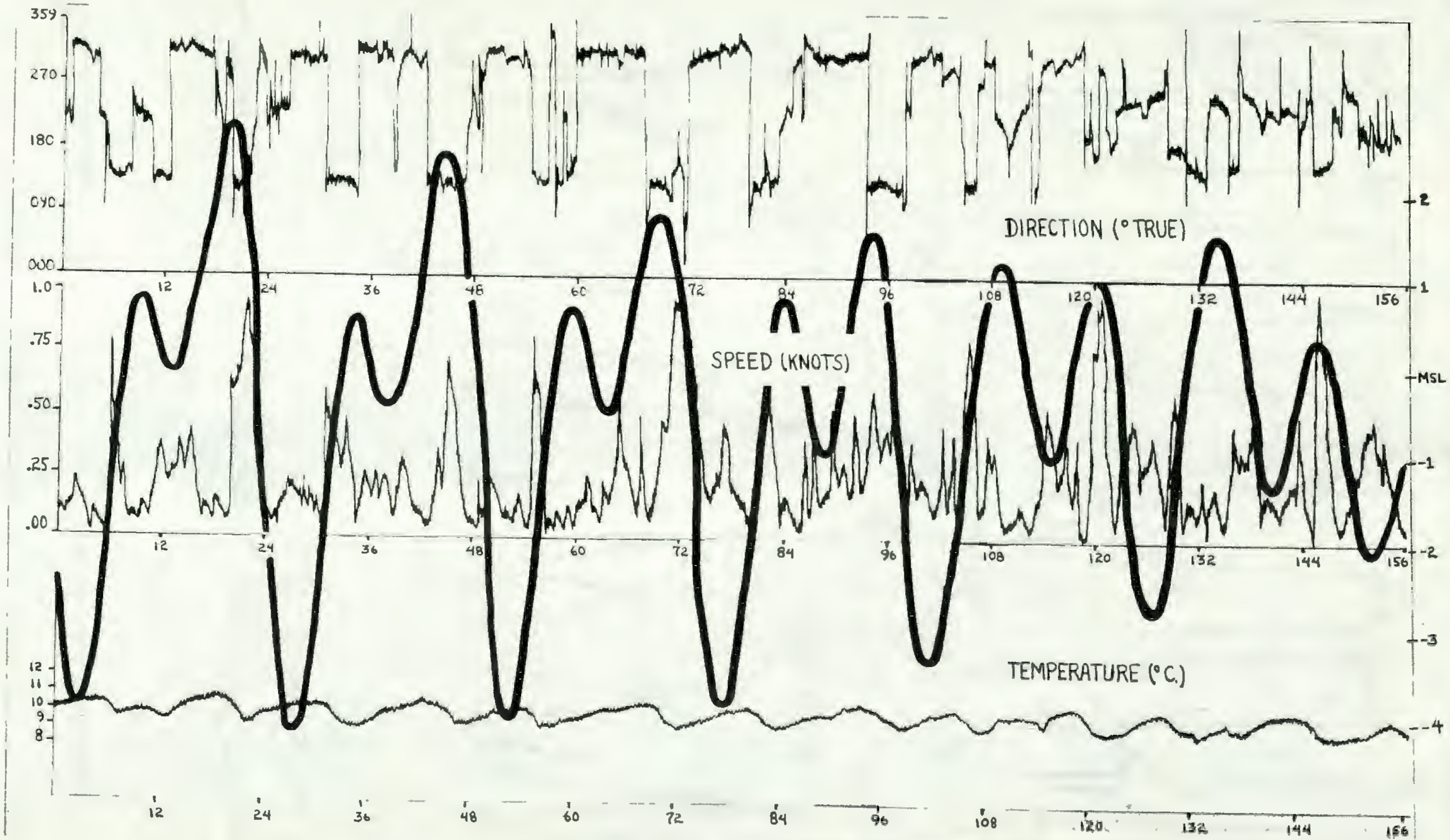

FIGURE 6. DISPLAY OF JANUARY TIME SERIES
MARIGRAM SUPERIMPOSED

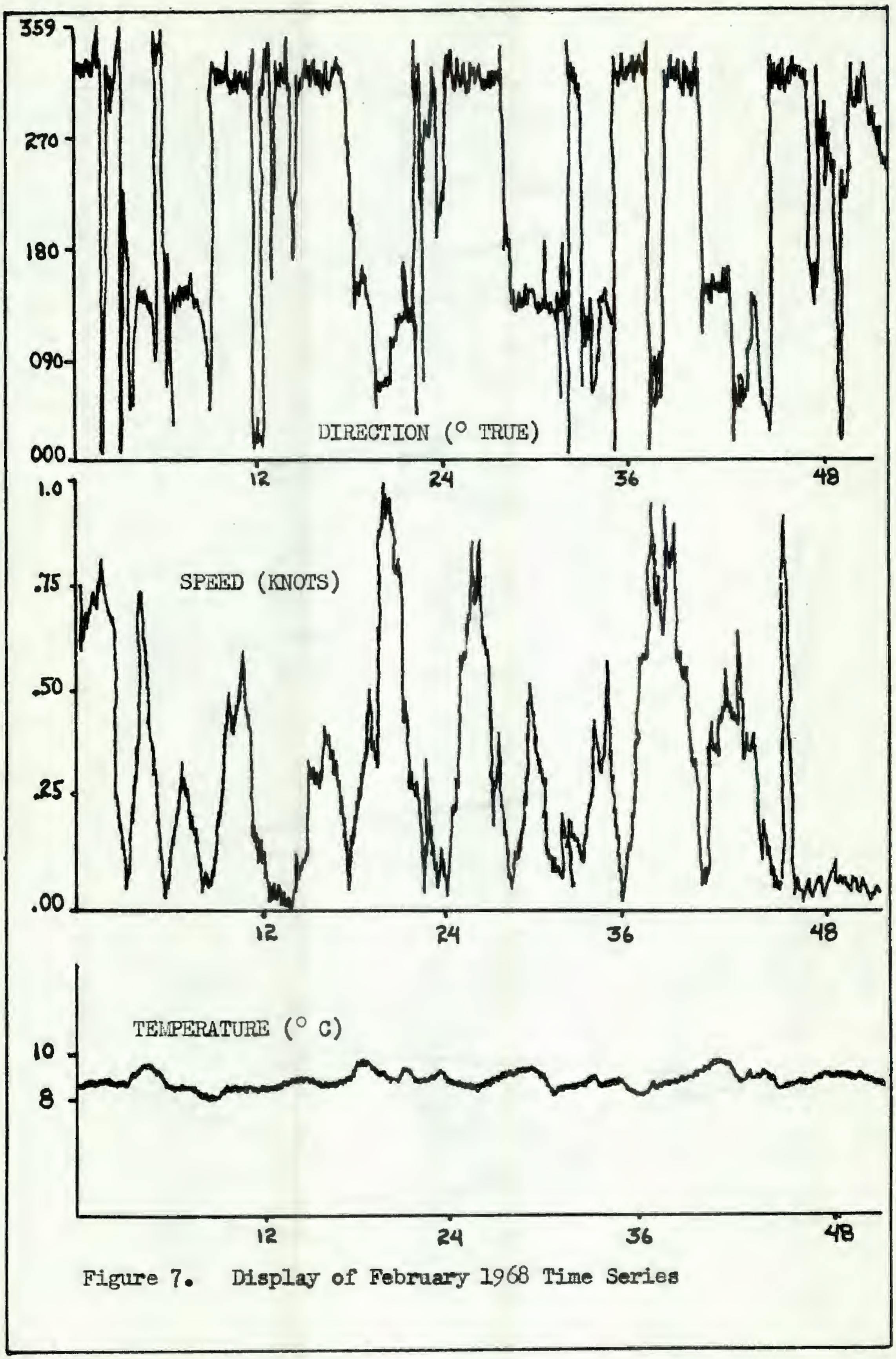

Figure 7. Display of February 1968 Time Series

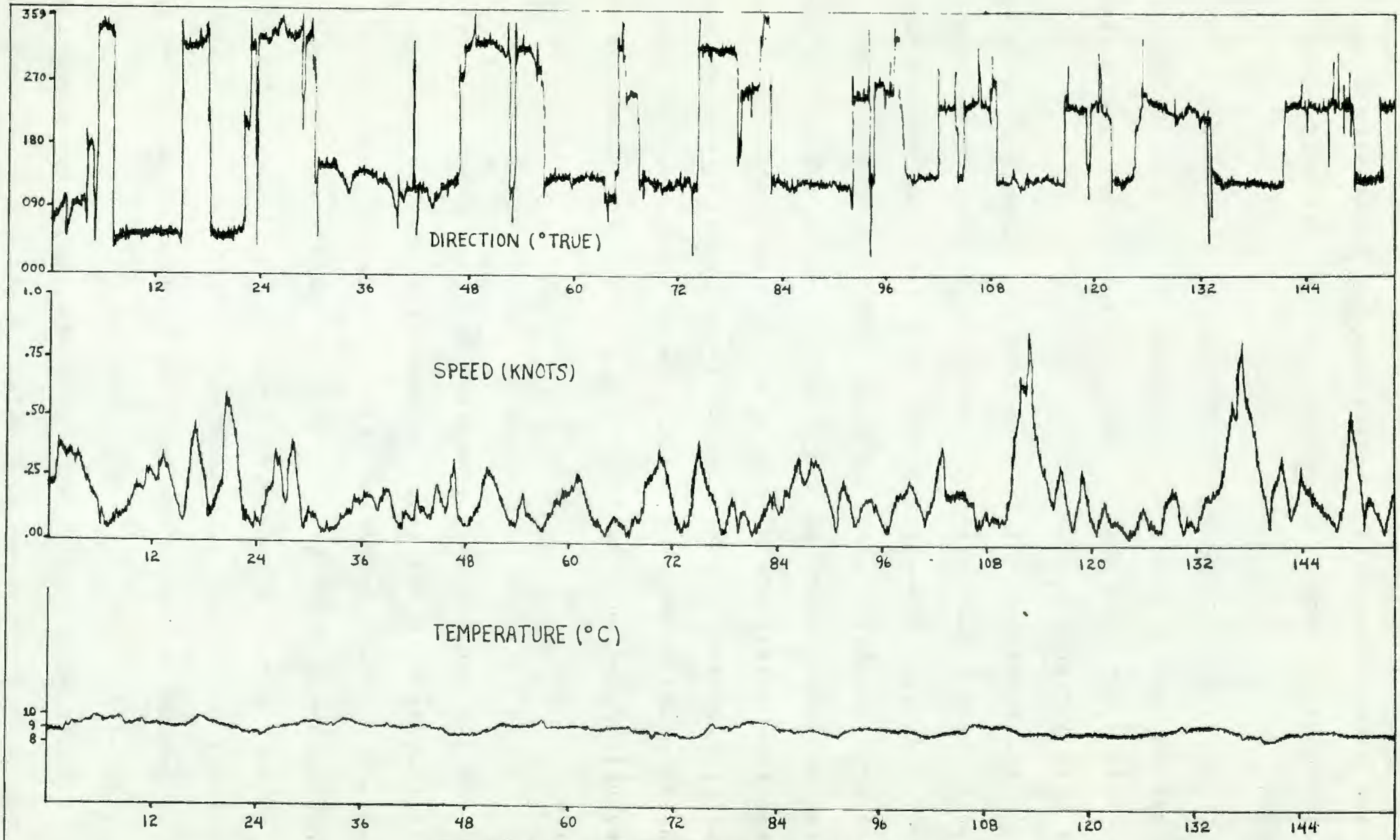

FIGURE 8. DISPLAY OF MAY 1968 TIME SERIES

These water temperature characteristics agree with seasonal data for this location reported by Keene and Middelburg (1967, 1968).

The frequency distributions of current speed all show skewness towards lower speeds. Mode values vary between 0.08 knot and 0.15 knot. Speeds were recorded over a range of 0 to 1.0 knot.

The distributions of direction of the current show wide variability between records. The single mode in November 1967 indicates down-canyon flow during most of the recording period. April 1967, January 1968, and February 1968 frequency distributions are clearly bimodal indicating current reversals. The direction of flow is predominantly along the approximate canyon axis, however, other direction frequency peaks do exist. Variations in topography at the measuring station almost certainly affect the current direction.

Table III shows a summary of the elementary statistics of the current for the seven time series. The mean temperatures agree with the seasonal means for the region while an overall standard deviation of the temperature values is approximately 0.5 degrees. Current speed averages about 0.23 knot with a standard deviation of 0.17 knot. The high variance of current direction reflects the variability of this parameter and agrees with the multimodal character of the direction frequency distributions.

Power spectra of the temperature, speed and direction time series are shown in Figures 12, 13 and 14 respective-

TABLE III
Summary of Current Statistics

TEMPERATURE (degrees Celsius)

Date	Hours	Mean	Median	Mode	Variance (degrees)^2	Std.Dev.
Mar 67	50	8.3	8.3	8.3(41.2)	0.29	0.54
Apr 67	28	8.6	8.5	8.7(68.9)	0.06	0.24
Nov 67	56	11.5	11.3	10.8(14.3)	0.20	0.47
Jan 68	153	9.9	10.0	10.1(16.7)	0.84	0.92
Feb 68	52	8.9	8.9	8.9(24.3)	0.22	0.49
Apr 68	5	8.5	8.5	8.5(83.3)	0.01	0.08
May 68	162	9.0	9.0	9.0(29.4)	0.19	0.43

SPEED (knots)

Date	Hours	Mean	Median	Mode	Variance (knots)^2	Std.Dev.
Mar 67	50	0.18	0.17	0.10(17.2)	0.01	0.11
Apr 67	28	0.21	0.15	0.15(26.6)	0.04	0.20
Nov 67	56	0.27	0.21	0.08(17.0)	0.04	0.20
Jan 68	153	0.22	0.18	0.15(18.7)	0.03	0.16
Feb 68	52	0.31	0.25	0.08(11.2)	0.06	0.24
Apr 68	5	0.11	0.10	0.10(46.2)	0.01	0.09
May 68	162	0.17	0.15	0.10(24.4)	0.02	0.12

DIRECTION (degrees true)

Date	Hours	Mean	Median	Mode	Variance (degrees)^2	Std.Dev.
Mar 67	50	286	275	300(18.9)	9241	96
Apr 67	28	178	275	320(22.3) 150(14.7)	8361	92
Nov 67	56	230	230	235(52.0)	1472	38
Jan 68	153	224	250	310(31.1) 130(17.7)	5638	75
Feb 68	52	004	205	325(24.3) 145(18.7)	10949	105
Apr 68	5	097	095	095(39.6)	274	17
May 68	162	135	140	135(30.4) 235(13.9) 310(12.1) 050(8.8)	7725	88

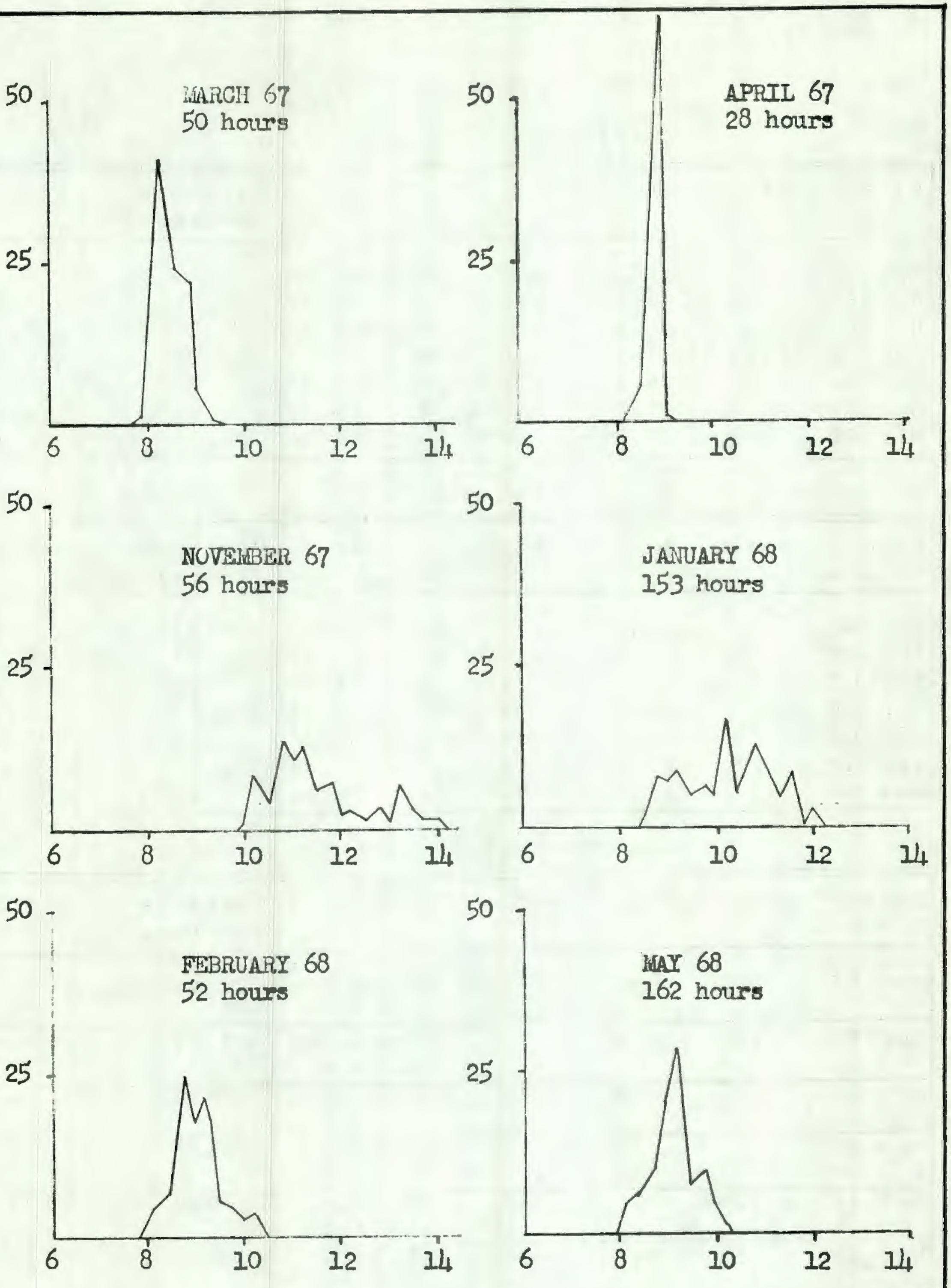

Figure 9. Frequency distribution of Temperature.
(per cent of data vs. temperature in degrees Celsius)

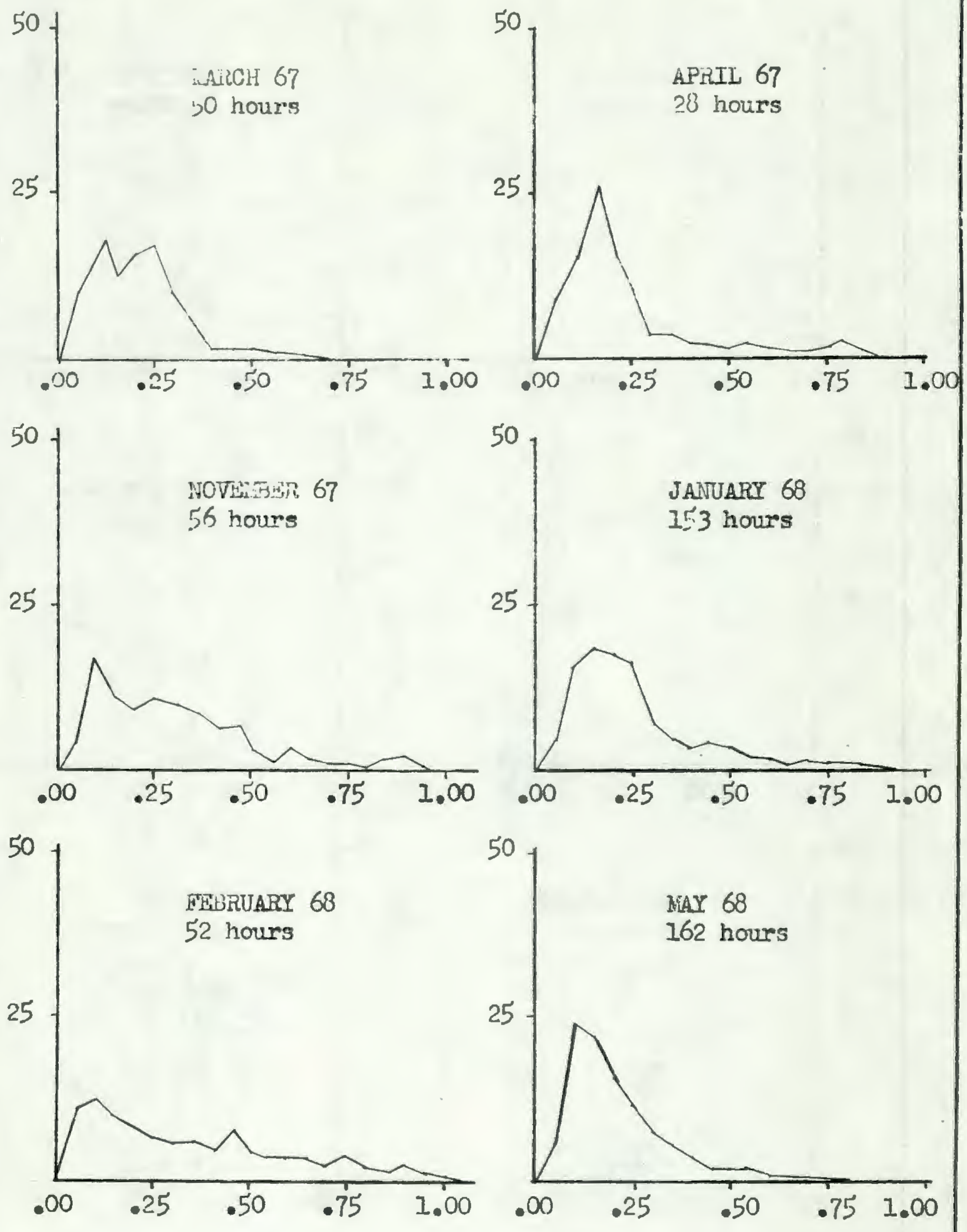

Figure 10. Frequency Distribution of Speed
(per cent of data vs. speed in knots)

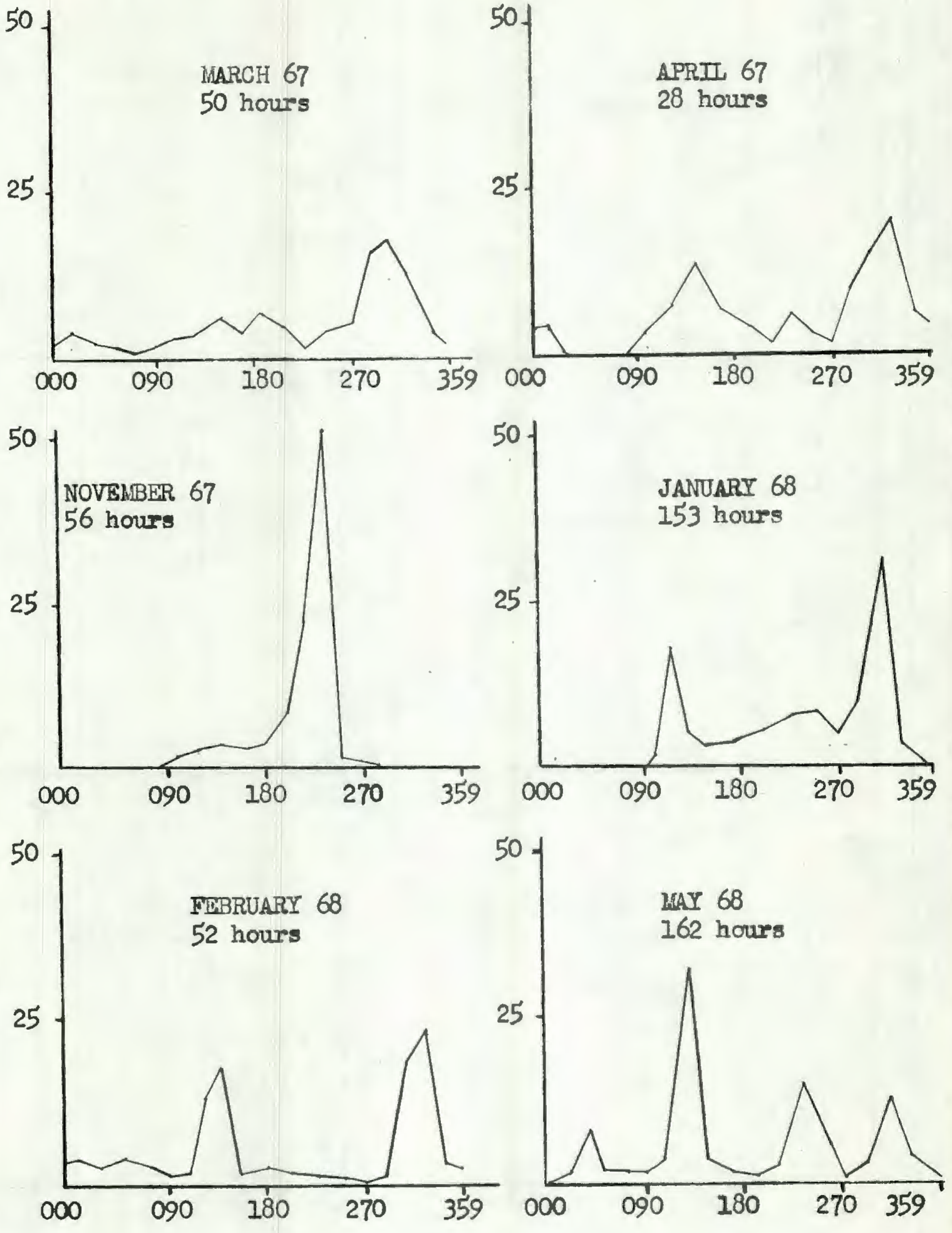

Figure 11. Frequency Distribution of Direction
(per cent of data vs. direction in degrees true)

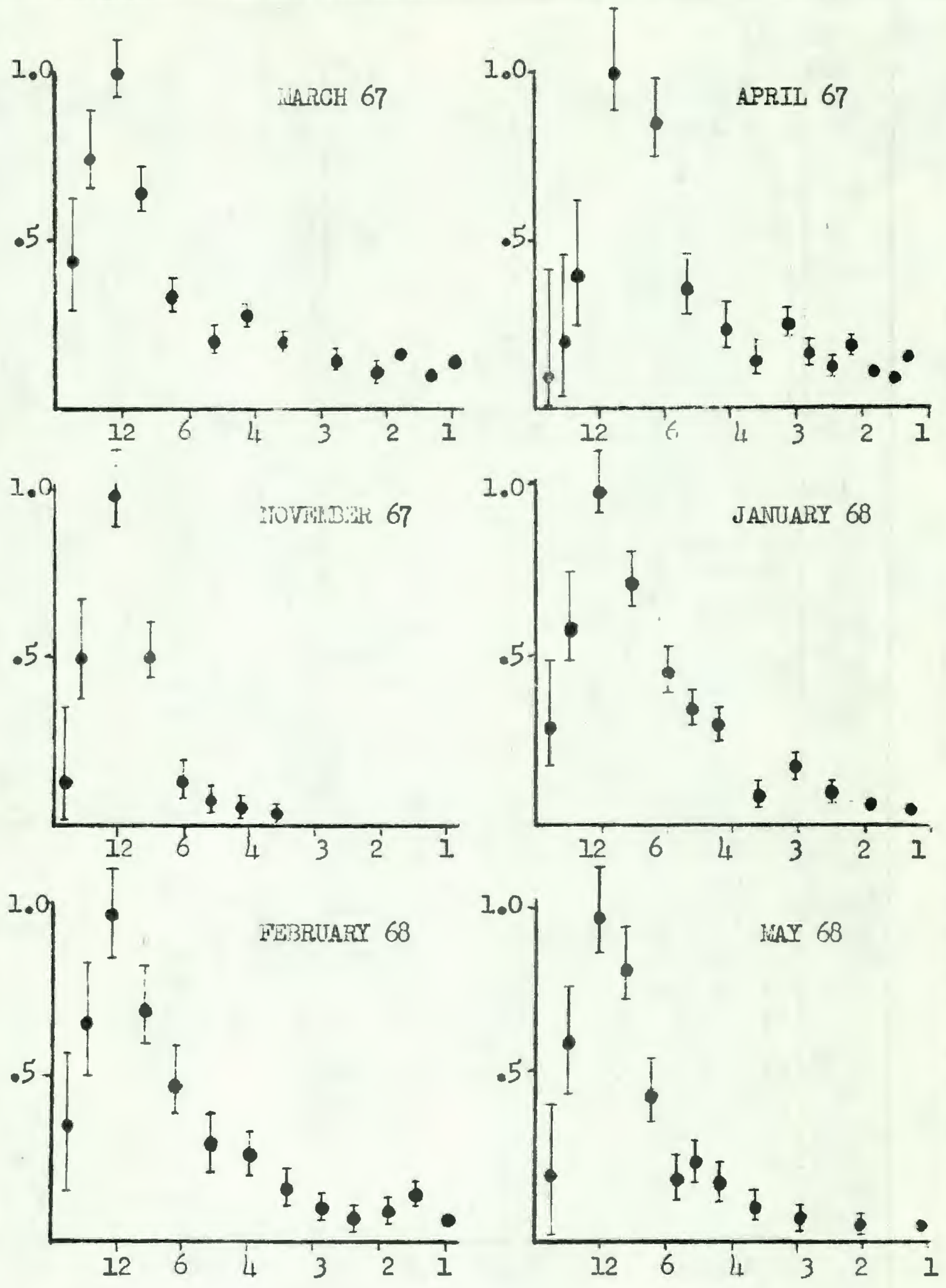

Figure 12. Power Spectra of Temperature
(normalized energy density vs. period in hours)

⧫ 90 per cent confidence interval

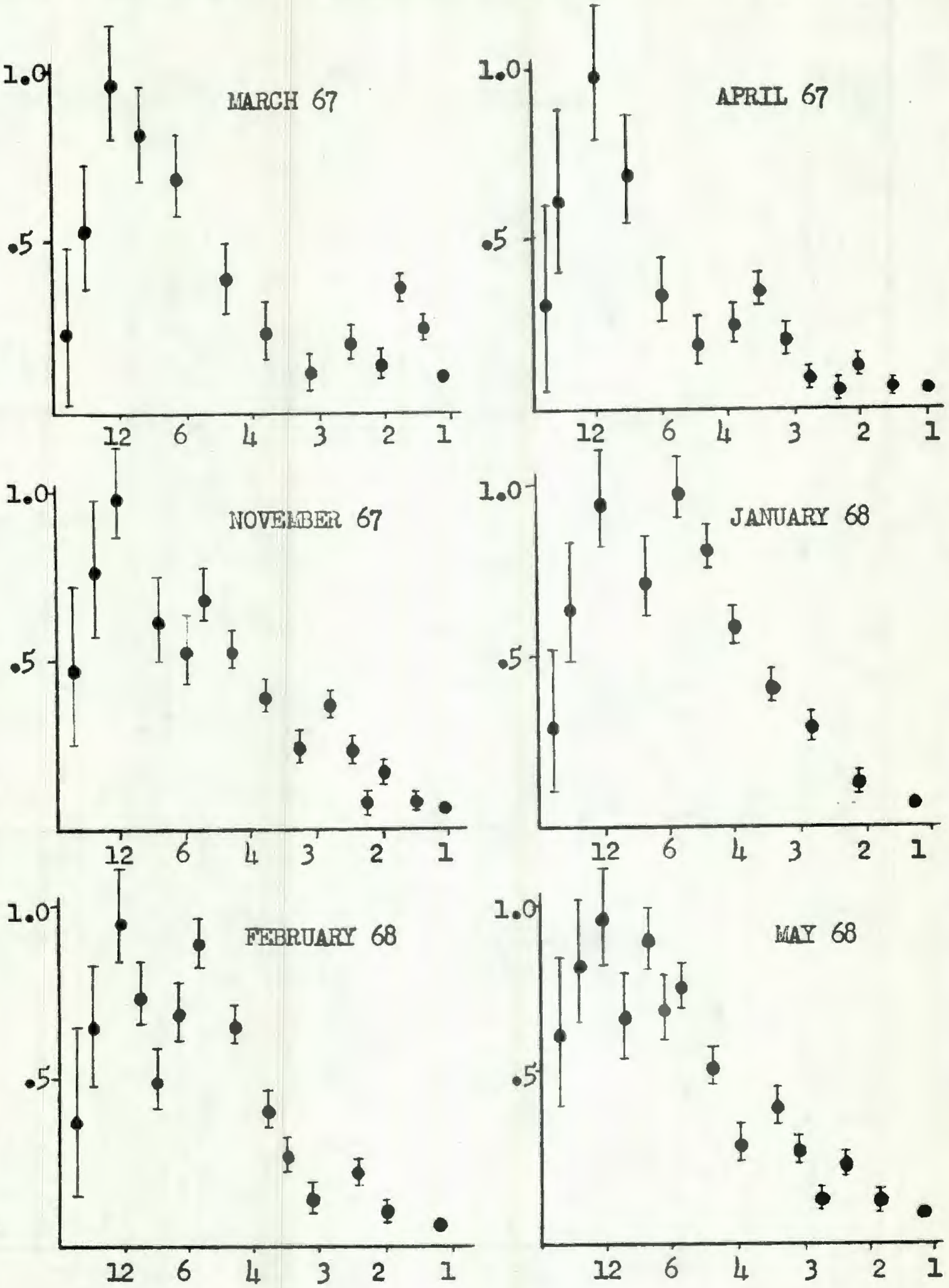

Figure 13. Power Spectra of Speed
(normalized energy density vs. period in hours)

● 90 per cent confidence interval

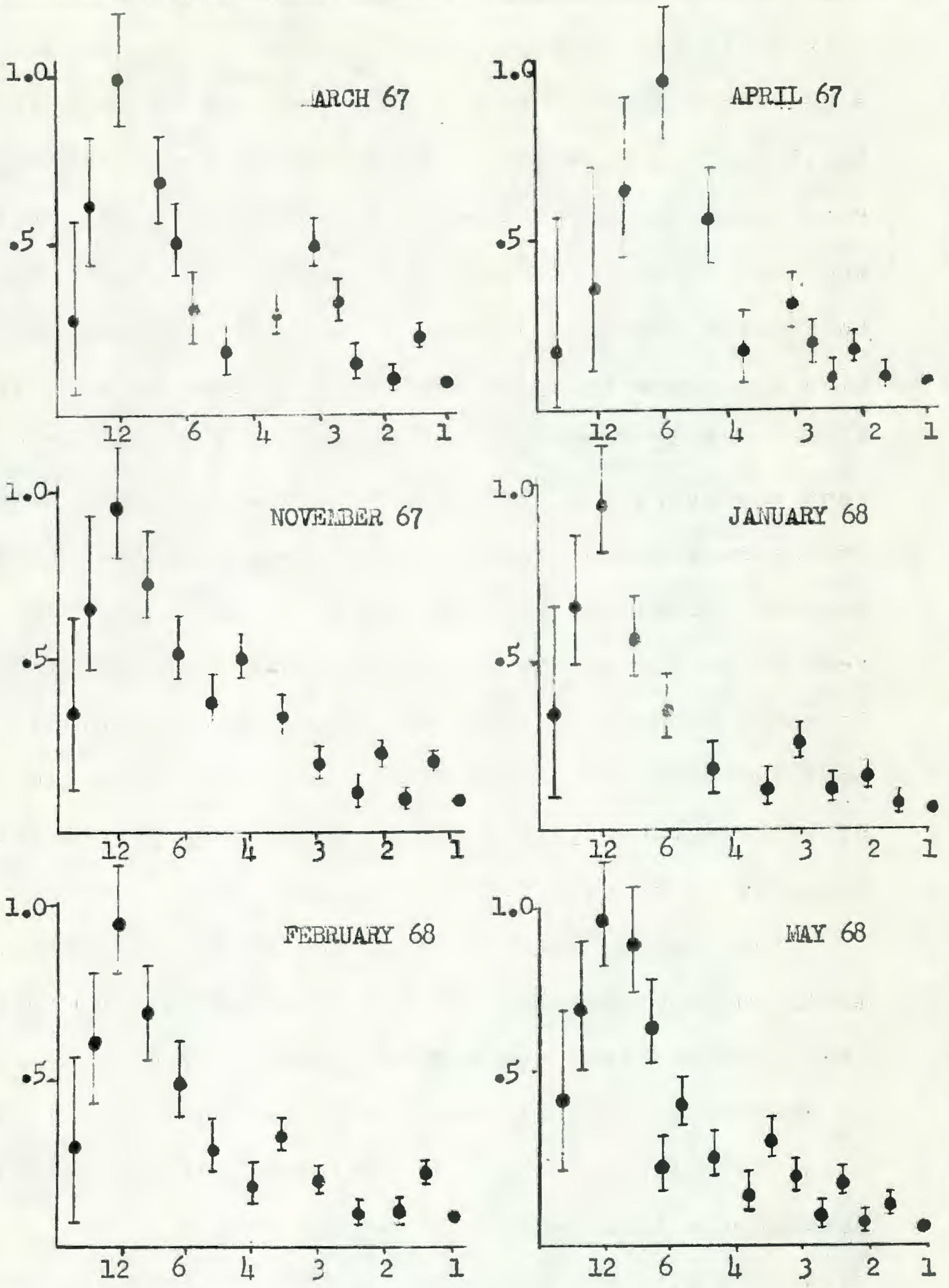

Figure 14. Power Spectra of Direction (normalized energy density vs. period in hours)

90 per cent confidence interval

ly. The spectral estimates of temperature show a prominent peak at 12 hours in all records except April 1967 which shows a peak at 8 hours. This 8 hour peak may be in error as the April 1967 time series covered only 28 hours. The power spectra of the speed time series all show peaks at 12 hours and also indicate considerable energy in periods between 4 to 6 hours and 2 to 3 hours. Spectral estimates of direction also show the prominent 12 hour peak as well as significant energy in periods between 2 to 4 hours. The consistent energy peak at 12 hours indicates a strong association of the measured parameters with the semidiurnal tidal component. Speed oscillations of 4 to 6 hour periods would seem to depend on the strength of the semidiurnal component. It seems reasonable that the current speed would exhibit an oscillation at twice the tidal frequency since, ideally, a current responding to a strong semidiurnal tidal force would pulse twice between tidal maxima.

The direct correlation of the canyon currents and the marigram from Monterey Bay was examined for the November 1967, January 1968 and February 1968 records. The marigram is sketched on the January record in Figure 6. In this record there appears to be no clear-cut, direct relationship between the tidal movement and the canyon current. The direction of flow, while cyclic in character, appears to show only qualitative correlation with the tidal movement. Peak speeds appear to show good correlation with periods of maximum flood and ebb but this relationship becomes vague after about four days. The other two records show similar behavior.

Extremely rapid speed changes were characteristic features of all records. The high speed bursts generally reached maximum speed within three minutes of their initiation. A speed increase of 0.80 knots was recorded in a 1.5 minute period in November 1967, After attaining maximum speed a slow decrease usually occured after 20 to 30 minutes. Sustained speeds in excess of 0.80 knot were observed on several occasions to continue for at least one hour.

VI. CONCLUSIONS AND RECOMMENDATIONS

Accurate continuous current measurements 15 meters above the bottom at the head of Monterey Canyon have been collected. The measurements have been discussed in the previous chapter. The need for an even longer series of current measurements in submarine canyons still exists. The validity of near-bottom current data is enhanced by the use of a taut wire mooring which eliminates the problem of induced motion in surface moors.

This investigation has shown that currents in the head of Monterey Canyon are responsive to the tidal cycle. Movement of colder water in an up-canyon (coastward) direction appears in a number of instances in the records examined. This water motion is strongly associated with the semidiurnal constituent of the tide. A typical 12 hour current cycle consists of high speed (0.75 knot)bursts of cold water moving up-canyon along the canyon axis. As the upwelling cold water slows to a stop, a warmer down-canyon current reverses the current direction. Power spectral analysis indicates a dominant period of current motion at about 12 hours. The precise relationship between the tidal movement and the canyon currents is not fully understood and should be the subject of further study.

Current speed in Monterey Canyon appears to be somewhat higher than speeds previously measured in this canyon and in others. In all cases where the length of the observation covered at least one full tidal cycle, speeds in excess of

0.60 knot were measured. Rapid speed changes occur at frequent intervals with speeds greater than 0.80 knot sustained for periods of up to one hour.

Although it appears that the tide is the dominant factor in currents in the head of the canyon, the appearance of subtidal oscillatory frequencies in most spectra would indicate other short-period cyclic processes modifying the current. Sub-tidal oscillations of 19 to 39 minutes have been reported in Monterey Bay (Raines, 1967). A more detailed analysis of these oscillations would be possible if that part of the spectra responsive to tide were filtered out of the record and the residual current studied. Resolution in the unfiltered power spectra does not permit the author to examine this feature.

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APPENDIX A

```
C. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
C
C     PROGRAM CURRENT
C
C        THIS PROGRAM PROVIDES ELEMENTARY STATISTICS FOR THREE TIME
C     SERIES OF CURRENT TEMPERATURE, SPEED, AND DIRECTION.  MEANS ARE
C     COMPUTED HOURLY, DAILY AND FOR THE ENTIRE SERIES.  A HISTOGRAM
C     IS PROVIDED DAILY AND FOR THE SERIES.  VARIANCE AND STANDARD
C     DEVIATION ARE COMPUTED FOR THE SERIES.  OPTIONAL GRAPHICAL OUTPUTS
C     OF THE COMBINED TEMPERATURE, SPEED, AND DIRECTION SERIES AND
C     HISTOGRAMS ARE PROVIDED.
C
C
      DIMENSION DATE(3),DATO(3)
      DIMENSION TIME(2600),A(2600),HR(200),B(2600),C(2600)
      DIMENSION T(2600),S(2600),D(2600),M(2600)
      REAL*8 ITITLE(12)
      REAL LABEL/4H    /
      CLOCK=ITIME(0)*0.01
C     PROVIDE TITLE FOR TEMP,SPEED,DIRECTION DISPLAY
C     TITLE IS TWO CARDS CONTAINING NO MORE THAN 48 CHARACTERS (6A8)
      READ(5,105)(ITITLE(I),I=1,12)
C     CONTROL CARD INPUT:
      READ(5,202)NN,NO,NT,NA,NH,NP,PN,NW,PW,ICOR,IMO,DATE,DATO
C       NN=NO. OF DATA POINTS; CALL DRAW MUST BE ADJUSTED
C            TO TOTAL OF NN POINTS(I4)
C       NO=DAY OF FIRST OBSERVATION(I2)
C       NT=TIME OF FIRST OBSERVATION(I4)
C       NA=LARGEST NT LESS THAN 2400(I4)
C       NH=HOUR FRACTION(IN MIN.) OF FIRST OBS. (I2)
C       NP=LATITUDE DEGREES(I2)
C       PN=LATITUDE MINUTES (F6.2)
C       NW=LONGTITUDE DEGREES(I3)
C       PW=LONGTITUDE MINUTES(F6.2)
C       ICOR=DIRECTION CORR. FOR MAGNETIC VAR. OR DEV. (I3)
C       IMO=LAST DAY OF MONTH(I3)
C       DATE=MONTH OF OBSERVATION(3A4)
C       DATO=DATE PLUS ONE MONTH(3A4)
      DEL=3.75
C     DEL IS THE SAMPLING INTERVAL IN MINUTES
      TIME(1)=0.
      NODRW=0
C     NODRW=1 IF GRAPHS ARE NOT DESIRED
      L=0
      NZ=0
      IDAY=1
      WRITE(6,104)NP,PN,NW,PW,NO,NT,DATE
      WRITE(6,100)
      WRITE(6,106)NO,NT,DATE
C     INPUT TEMP, SPEED, AND DIRECTION TIME SERIES
      DO 5 I=1,NN,5
      READ(5,200,END=55)(T(I+K),S(I+K),M(I+K),K=0,4)
    5 CONTINUE
   55 CONTINUE
C     ADJUST DIRECTION IF REQUIRED
   41 DO 10 I=1,NN
      M(I)=M(I)+ICOR
      IF(M(I)-0.)42,43,43
   42 M(I)=M(I)+360
   43 CONTINUE
      N=I
      IF(T(I).EQ.1.)GO TO 10
    7 WRITE(6,101)TIME(I),T(I),S(I),M(I),I
      IF(L.LT.16)GO TO 8
      NT=NT+100
      IF(NT.LE.NA)GO TO 56
      NT=0000+NH
      NO=NO+1
      IMN=I-NZ
C     AT END OF EACH DAY COMPUTE STATISTICS
      CALL DAY(T,S,M,IMN,I,1,DTAV,DSAV,DDAV)
      IDDAV=IFIX(DDAV)
      WRITE(6,88)IDAY,DTAV,DSAV,IDDAV
   88 FORMAT(5X,'DAY ',I2,' STATISTICS:    AVGDAYTEMP=',F6.2,3X,
     1'AVGDAYSPD=',F5.2,3X,'AVGDAYDIR=',I4,//)
      IDAY=IDAY+1
   87 CONTINUE
      NZ=0
C     IF MONTH CHANGES REPLACE THE DATE
   56 IF(NO.LE.IMO)GO TO 3
      NO=1
      DO 60 J=1,3
   60 DATE(J)=DATO(J)
    3 CONTINUE
      HR(I)=TIME(I)/60.
      IF(I.GE.18)GO TO 11
      IML=I-L
      GO TO 12
   11 CONTINUE
      IML=I-L+1
   12 CONTINUE
C     CALL SUBROUTINES FOR HOURLY MEANS
      CALL MEAN(T,IML,I,AT )
      CALL MEAN(S,IML,I,AS )
      CALL MEAND(M,IML,I,S,AVG)
      MD=IFIX(AVG)
      IF(MD.GE.0)GO TO 58
      MD=360+MD
   58 CONTINUE
C     WRITE OUT THE HOURLY MEANS
      WRITE(6,103)NO,NT,DATE,HR(I),AT,AS,MD
      L=0
    8 TIME(I+1)=TIME(I)+DEL
      NZ=NZ+1
      L=L+1
      C(I)=T(I)/2.
   10 CONTINUE
      N=NN
C     SET SCALES FOR GRAPHICAL DISPLAY
      DO 201 I=1,N
      TIME(I)=TIME(I)/60.
      A(I)=(FLOAT(M(I))/24.)+30.
  201 B(I)=(S(I)*15.)+15.
      IF(NODRW.EQ.1)GO TO 85
C     DRAW THE COMBINED TEMP,SPEED,AND DIRECTION GRAPH
      CALL DRAW( NN,C,TIME,1,0,LABEL,ITITLE,5.,300.,0,0,2,2,9,15,1,LAST)
      CALL DRAW( NN,B,TIME,2,0,LABEL,ITITLE,5.,300.,0,3,2,2,9,15,1,LAST)
      CALL DRAW( NN,A,TIME,3,0,LABEL,ITITLE,5.,300.,0,6,2,2,9,15,1,LAST)
   85 CONTINUE
C     COMPUTE THE TIME SERIES MEANS
      CALL MEAN(T,1,N,TAT)
      CALL MEAN(S,1,N,TAS)
      CALL MEAND(M,1,N,S,AVG)
      MMD=IFIX(AVG)
      IF(MMD.GE.0)GO TO 57
      MMD=360+MMD
   57 CONTINUE
      WRITE(6,107)TAT,TAS,MMD
      DO 16 I=1,N
   15 D(I)=FLOAT(M(I))
   16 T(I)=C(I)*2.
C     CALL HISTO SUBROUTINE FOR TIME SERIES HISTOGRAM
      CALL HISTO(5.,16.,44,T,NN,1,NODRW)
      CALL HISTO(0.,1.,20,S,NN,1,NODRW)
      CALL HISTO(0.,360.,36,D,NN,1,NODRW)
```

```
C     CALL POWER SUBROUTINE FOR RMS,VARIANCE, AND STANDARD DEVIATIONS
      CALL POWER (DEL,NN,T,S,D,100)
      CLOCK=ITIME(0)*0.01-CLOCK
      WRITE(6,999)CLOCK
  105 FORMAT(6A8)
  202 FORMAT(I4,I2,2I4,2I2,F6.2,I3,F6.2,2I3,3A4,3A4)
  104 FORMAT(1H1,T40,'CURRENT DATA OBTAINED IN MONTEREY CANYON',///,5X,
     5'METER POSITION:  ',
     1I2,F6.2,' N  ',I3,F6.2,' W',/,5X,'ZERO TIME: ',I2,I4,'(LOCAL)',
     2 3A4,//,5X,'TIME IN MINUTES',/,5X,'TEMPERATURE IN DEGREES CENTIGRA
     3DE',/,5X,'CURRENT SPEED IN KNOTS ',/,5X,'CURRENT DIRECTION IN DEGR
     4EES TRUE',////)
  100 FORMAT(15X,'TIME',10X,'TEMPERATURE',6X,'CURRENT SPEED',
     14X,'CURRENT DIRECTION')
  106 FORMAT(1H0,5X,I2,I4,3A4)
  200 FORMAT(5(F5.1,F5.2,I4))
  101 FORMAT(     10X,F10.2,13X,F4.1,15X,F5.2,14X,I3,5X,I5)
  103 FORMAT(1H0,I3,I4,3A4,2X,F5.1,'HRS',4X,'MEAN TEMP:',
     1F6.2,4X,'MEAN SPEED:',F5.2,2X,'MEAN DIR:',I3,//)
  107 FORMAT(1H0,11X,'MEANS FOR THIS RECORD:   TEMP:',F6.2,2X,'SPEED:',
     1F5.2,2X,'DIRECTION:',I3)
  999 FORMAT(///,T80,'ELAPSED COMPUTING TIME=',F15.7,'SECONDS')
      STOP
      END



      SUBROUTINE MEAN(A,J,M,AVG)
C     THIS SUBROUTINE COMPUTES THE ARITHMETIC MEAN OF
C     ANY INPUT PARAMETER.
      DIMENSION A(2600)
      AVG=0.0
      SUM=0.0
      KK=M-J+1
      FKK=FLOAT(KK)
      DO 1 K=J,M
    1 SUM=SUM+A(K)
      AVG=SUM/FKK
      RETURN
      END
      SUBROUTINE MEAND(LL,J,M,S,AVG)
C     THIS SUBROUTINE COMPUTES THE MEANS OF DIRECTIONS INPUT AS
C     COMPASS HEADINGS BY SUMMING SINES AND COSINES, CONVERT
C     TO VECTOR WITH SPEED, THEN NORMALIZE AND FIND THE
C     ARCTANGENT.  THIS PROCEDURE NECESSARY TO CIRCUMVENT THE
C     000 TO 360 DISCONTINUITY.
      DIMENSION L(2600),A(2600),LL(2600)
      DIMENSION S(2600)
      SUM1=0.0
      SUM2=0.0
      DO 1 K=J,M
      L(K)=LL(K)
      A(K)=L(K)*.01745329
      IML=M-J+1
      XX=SIN(A(K))
      YY=COS(A(K))
      SUM1=SUM1+S(K)*SIN(A(K))
      SUM2=SUM2+S(K)*COS(A(K))
    1 CONTINUE
      U=SUM1/FLOAT(IML)
      V=SUM2/FLOAT(IML)
      USQ=U**2
      VSQ=V**2
      SUMSQ=USQ+VSQ
      VAVG=SQRT(SUMSQ)
      X=U/V
      AVG=ATAN2(U,V)
      AVG=AVG/.01745329
      RETURN
      END
```

```
      SUBROUTINE HISTO(A,Z,K,X,L,M,NODRW)
C     THIS SUBROUTINE OBTAINS HISTOGRAM, PERCENT OF DATA PER
C     INTERVAL, PROBABILITY DENSITY, AND PROBABILITY DISTRIBUTION.
C     ENTER WITH: A=LOWER BOUND
C                 Z=UPPER BOUND
C                 K=NO.INTERVALS(MAX=50)
C                 X=VARIABLE NAME
C                 L=NO.VARIABLES(MAX=3000)
```

```
C               NODRW=1 (IF GRAPH NOT DESIRED)
      DIMENSION N(2600),X(2600),P(55),PP(55),D(55),PD(55),B(2600)
      REAL*8 ITITLA(12)
      REAL LABEL/4H    /
      IF(NODRW.EQ.1)GO TO 12
      READ(5,105)(ITITLA(I),I=1,12)
   12 CONTINUE
      WRITE(6,101)
      LL=0
      C=(Z-A)/FLOAT(K)
      D(1)=A
      KP1=K+1
      KP2=K+2
      DO 1 I=2,KP2
      IM1=I-1
    1 D(I)=A+IM1*C
      SUMP=0.0
      DO 5 I=1,KP2
    5 B(I)=0
      LLL=M+L
      DO 2 J=M,LLL
      DO 3 I=1,KP2
      IP1=I+1
      IF(X(J).LT.D(I))GO TO 3
      IF(X(J).GE.D(I))GO TO 4
    4 IF(X(J).LT.D(IP1))GO TO 10
      GO TO 3
   10 B(I)=B(I)+1.
      LL=LL+1
      IF(X(J).LE.Z)GO TO 3
      LL=LL-1
    3 CONTINUE
    2 CONTINUE
      DO 6 I=1,KP2
    6 P(I)=B(I)/FLOAT(LL)
      DO 7 I=1,KP2
    7 PP(I)=P(I)/C
      DO 8 I=1,KP2
      SUMP=SUMP+PP(I)
    8 PD(I)=SUMP*C
      DO 9 I=1,KP1
      IP1=I+1
      N(I)=IFIX(B(I))
      WRITE(6,100)I,D(I),D(IP1),N(I),P(I),PP(I),PD(I)
    9 CONTINUE
```

```
  101 FORMAT(1H0,10X,'INTERVAL',11X,'OCCURRENCES',3X,'% DATA',3X,
     1'DENSITY',3X,'DISTRIBUTION',//)
  100 FORMAT(4X,I2,F7.2,' - ',F7.2,4X,I8,3F12.3)
      WRITE(6,103)LL
  103 FORMAT(//,8X,'NUMBER OF POINTS :    ',I8)
  105 FORMAT(6A8)
      DO 11  I=1,KP1
   11 D(I)=D(I)+(C/2.)
      IF(NODRW.EQ.1)RETURN
      CALL  DRAW(KP1,D,B,0,0,LABEL,ITITLA,0,0,0,0,0,0,9,7,0,LAST)
      RETURN
      END




      SUBROUTINE POWER (DEL,N,X,Y,Z,L)
C     THIS SUBROUTINE COMPUTES MEANS, MEAN SQUARED VALUES AND
C     STANDARD DEVIATIONS OF THREE INPUT TIME SERIES.
      DIMENSION XM(2600),YM(2600),ZM(2600),
     1CXX(200),CYY(200),CZZ(200),RX(200),RY(200),RZ(200),GX(200),
     2GY(200),GZ(200),                               RT(200),RS(200),
     3RD(200),CCVT(200),CCVS(200),CCVD(200)
      DIMENSION X(2600),Y(2600),Z(2600),M(2600)
C  ENTER WITH:      DEL=SAMPLING INTERVAL IN MINUTES
C                   N=NUMBER OF SAMPLES (MAX.=3000)
C                   X=VARIABLE OF THE FIRST SERIES
C                   Y=VARIABLE OF THE SECOND SERIES
C                   Z=VARIABLE OF THE THIRD SERIES
C                   L=NUMBER OF LAGS (MAX.=200)
C     CALCULATION OF SERIES MEAN VALUE
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      DO 2  I=1,N
      SUM1=SUM1+X(I)
      SUM2=SUM2+Y(I)
    2 SUM3=SUM3+Z(I)
      XBAR=SUM1/N
      YBAR=SUM2/N
      ZBAR=SUM3/N
      WRITE(6,3)XBAR,YBAR,ZBAR
    3 FORMAT(T10,'SAMPLE MEANS:',//T35,'XBAR= ',F10.3,/,T35,'YBAR= ',
     1F10.3,/,T35,'ZBAR= ',F10.3,///)
```

```
C     TRANSFORMATION TO ZERO MEAN VALUE
      DO 4 I=1,N
      XM(I)=X(I)-XBAR
      YM(I)=Y(I)-YBAR
      ZM(I)=Z(I)-ZBAR
    4 CONTINUE
      CALL MEAN(XM,1,N,AVG)
      WRITE(6,15)AVG
   15 FORMAT(T40,F30.10)
      CALL MEAN(YM,1,N,AVG)
      WRITE(6,15)AVG
      CALL MEAN(ZM,1,N,AVG)
      WRITE(6,15)AVG
C     CALCULATION OF THE MEAN SQUARE VALUE
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
      DO 5 I=1,N
      SUM1=SUM1+(XM(I))**2
      SUM2=SUM2+(YM(I))**2
    5 SUM3=SUM3+(ZM(I))**2
      XMS=SUM1/N
      YMS=SUM2/N
      ZMS=SUM3/N
      WRITE(6,6)XMS,YMS,ZMS
    6 FORMAT(T10,'MEAN SQUARE VALUES:',//,T35,'XMSQ= ',F10.3,/,T35,
     1'YMSQ= ',F10.3,/,T35,'ZMSQ= ',F10.3,///)
C     CALCULATION OF THE STANDARD DEVIATION
      XTEMP=SUM1/(N-1)
      YTEMP=SUM2/(N-1)
      ZTEMP=SUM3/(N-1)
      SX=SQRT(XTEMP)
      YX=SQRT(YTEMP)
      ZX=SQRT(ZTEMP)
      WRITE(6,7)SX,YX,ZX
    7 FORMAT(T10,'STANDARD DEVIATIONS:',//,T35,'XSTDDEV= ',F10.5,/,T35,
     1'YSTDDEV= ',F10.5,/,T35,'ZSTDDEV= ',F10.5,///)
      RETURN
      END
      SUBROUTINE DAY(T,S,M,J,K,NODRW,DTAV,DSAV,DDAV)
C     THIS SUBROUTINE UTILIZES PREVIOUS SUBROUTINES TO OBTAIN
C     DAILY STATISTICS.
      DIMENSION TH(1000),SH(1000),DH(1000)
      DIMENSION T(2600),S(2600),D(2600),M(2600)
C     ENTER WITH:  T=TEMPERATURE SERIES
C                  S=SPEED SERIES
C                  M=DIRECTION SERIES
C                  J=DAY START OBSERVATION NUMBER
C                  K=TOTAL OBSERVATIONS IN THE SERIES
C                  NODRW=1 (IF GRAPH NOT DESIRED)
      CALL MEAN(T,J,K,DTAV)
      CALL MEAN(S,J,K,DSAV)
      CALL MEAND(M,J,K,S,DDAV)
      IF(DDAV.GE.0)GO TO 2
      DDAV=DDAV+360.
    2 CONTINUE
      JP1=J+1
      KK=K-JP1
      WRITE(6,3)JP1,K,KK
    3 FORMAT(2X,'DAILY HISTO FROM',I4,' TO ',I4,' TOTAL: ',I4,'PTS',//)
      DO 1 I=JP1,K
      TH(I)=T(I)
      SH(I)=S(I)
    1 DH(I)=FLOAT(M(I))
      CALL HISTO(5.,16.,44,TH,KK,J,NODRW)
      CALL HISTO(0.,1.,20,SH,KK,J,NODRW)
      CALL HISTO(0.,360.,36,DH,KK,J,NODRW)
      RETURN
      END
```

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13. ABSTRACT

An investigation of near-bottom currents in the head of Monterey Submarine Canyon was conducted between March 1967 and May 1968. Continous observations of water temperature, current speed and direction were obtained over periods ranging from 5 hours to 162 hours using an in situ Savonius rotor current measuring system. Basic statistical parameters and power spectra were calculated for each record. These revealed an average current speed of about 0.23 knot (standard deviation of 0.17 knot), and a current direction which indicates flow reversals predominantly along the canyon axis. Current and water temperature oscillations indicated a strong semidiurnal component. Water temperature changes also showed seasonal variation that agrees with the seasonal means of the region. Current speeds as high as 1 knot were measured.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

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